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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-01-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
15-11-2006	REPRINT	

4. TITLE AND SUBTITLE

Seeking radio emissions from hypervelocity micrometeoroid impacts: Early experimental results from the ground

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
63401F

5d. PROJECT NUMBER
5021

5e. TASK NUMBER
RS

5f. WORK UNIT NUMBER
A1

6. AUTHORS

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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29 Randolph Road
Hanscom AFB, MA 01731-3010

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RV-HA-TR-2008-1014

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVBXR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release; distribution unlimited.

13. SUPPLEMENTARY NOTES

Reprinted from *International Journal of Impact Engineering*, vol. 33 (2006) 781-787 © 2006 Elsevier Ltd.

14. ABSTRACT

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15. SUBJECT TERMS

Hypervelocity impacts   Radio emissions   Chamber experiments   Micrometeoroid

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Michael J. Starks
					19B. TELEPHONE NUMBER *(Include area code)*
UNCL	UNCL	UNCL	Unl	8	

Available online at www.sciencedirect.com
ScienceDirect
International Journal of Impact Engineering 33 (2006) 781–787
INTERNATIONAL JOURNAL OF IMPACT ENGINEERING
www.elsevier.com/locate/ijimpeng

Seeking radio emissions from hypervelocity micrometeoroid impacts: Early experimental results from the ground

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Available online 15 November 2006

Abstract

High-velocity impact experiments have been conducted to look for radio frequency (RF) emissions from impact-produced plasmas that could be used to identify micrometeoroid impacts to spacecraft in orbit. Launched by a three-stage light gas gun, 17 mm diameter by 0.9 mm thick Ti6Al-4V flyer plates impacted 0.75 mm thick indium (In) foil at more than $10\,\mathrm{km\,s^{-1}}$. The resulting collision presumably ionized some fraction of the vaporized In cloud, which was accelerated to about $12\,\mathrm{km\,s^{-1}}$. This weak In plasma then passed through a wide-band detection system that looked for RF emissions. Over the course of five shots during the experiment, no conclusive plasma emissions from the In were detected. However, strong evidence indicates that significant charge is accumulated on the flyer plate during acceleration and flight, possibly producing Paschen discharge to the chamber walls. Finally, plasma may be produced by the launcher secondary to launching the plate, leading to further contamination of the results. These effects have significant consequences for RF experiments attempted in launching systems of this type.

Keywords: Impact plasma; Hypervelocity; Micrometeoroid

1. Introduction

Several space experiments have observed and characterized the flux of high-velocity micrometeoroids of cometary origin in the Earth's orbit, e.g. Love and Brownlee [1]. Micrometeoroid debris poses an obvious mechanical damage hazard to space assets and may also precipitate a catastrophic electrical discharge that disrupts or disables onboard systems. However, when a satellite failure occurs, it is generally a diagnosis of exclusion that determines the cause to be an impact. Current impact detectors rely on micrometeoroids striking a dedicated small detector surface. Paradoxically, impacts to these surfaces by definition pose no risk to the satellite. An ideal detector would remotely sense impacts that occur anywhere on board, effectively using the entire spacecraft surface as a sensor. One possibility is to detect any radio frequency (RF) emissions from the plasma produced by the collision, as proposed by Foschini [2]. To evaluate the use of RF emissions

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doi:10.1016/j.ijimpeng.2006.09.044

from hypervelocity impact plasmas for remotely sensing collisions, the Air Force Research Laboratory has carried out limited high-velocity impact experiments using the three-stage light gas gun described by Chhabildas et al. [3,4] at the Sandia National Laboratories' Shock Thermodynamics Applied Research facility in New Mexico. The sections below describe the theoretical physics of the impact plasma, the apparatus, and the experimental results.

2. Micrometeoroid plasmas

A typical micrometeoroid of cometary origin might be of iron/carbon composition, 1 mm in diameter, 3 mg in mass, and traveling at $70\,\mathrm{km\,s^{-1}}$ in the target frame. When such an object impacts a spacecraft, it is traveling at a speed much greater than its internal sound speed, which is about $5\,\mathrm{km\,s^{-1}}$. As a consequence, a shock front sets up inside the meteoroid and information about the collision cannot travel to locations behind where vaporization is occurring. At this velocity, it takes approximately 10 ns to vaporize the entire micrometeoroid.

During this entire period of the impact, vaporized debris is produced from both the micrometeoroid and the target spacecraft. The processes governing the characteristics and behavior of this debris are described by Drapatz and Michel [5]. There is more than enough energy in the collision to produce 100% single ionization of the debris cloud, although the actual cloud probably has a large proportion of neutral atoms. Multiple ionizations are relatively rare. The resulting plasma is extremely dense (up to $10^{24}\,\mathrm{cm^{-3}}$ for the postulated micrometeoroid) but quite cold (5000–30,000 K). These conditions produce very high electron–ion, electron—neutral, and ion–neutral collision frequencies, causing 99% of the plasma to recombine in the first nanosecond, sometimes generating an optical flash. As the plasma cloud expands, it passes from a near-solid-state condition through the ideal gas stage. After this, collective effects begin to be felt as the Debye length becomes larger than the inter-particle distance and the plasma rapidly thermalizes its distribution function. At the end of the first nanosecond, the plasma cloud has expanded enough that the electron mean free path exceeds the cloud size, collisions drop nearly to zero, and the remaining 1% of ionization is "frozen in". While recombination is still occurring, the increasingly low rate of electron collisions disrupts local thermodynamic equilibrium by retaining the heat of recombination in the electron gas. The ions and atoms cool more quickly and further retard recombination. All of this takes place within about 1 mm of the impact site, depending on the assumed debris cloud velocity.

This process operates continuously as the micrometeoroid impactor vaporizes, which may take more than 10 ns. During this time, a largely collisionless plasma cloud continues to expand away from the impact site at speeds greater than $15\,\mathrm{km\,s^{-1}}$. It may radiate at the local plasma frequency as electrons in the cloud are prevented from running away from the slower ions by electrostatic forces. This frequency is inhomogeneous across the debris cloud, with a maximum near the point of impact, and changes rapidly as the cloud expands. When the shock front finally reaches the trailing edge of the impactor, the plasma generation, thermalization, and recombination processes cease. Any backward-moving rarefaction wave then serves to increase the rate of expansion of the plasma cloud. The collisionless cloud of plasma moves away from the site of impact and radiates at a host of changing plasma frequencies as it disperses into the vacuum. In addition, some further ionization may be produced by the secondary impact of ejecta with other spacecraft surfaces, although these impacts would only qualify as low velocity. Low-velocity impacts typically do not yield large amounts of ionization or high expansion velocities.

3. The experiment

Very little experimental work has been performed previously to measure RF emissions from impact plasmas. Crawford and Schultz [6] measured magnetic fields produced by light-gas gun impacts to try to explain remanent magnetization in meteoroid impact craters, but these data are at lower frequency than discussed above. There has been some study of blow-off plasmas from electrostatic discharge (ESD), e.g. Leung and Plamp [7], including RF emissions, but those plasmas form from collisions between vaporized material and electrons accelerated by strong electric fields produced in the discharge. Their characteristics may

be expected to be very different from those of plasmas produced by high-velocity impacts. An experiment dedicated to looking for RF emissions from impact plasmas was therefore required.

To produce an impact plasma similar to that generated by a hypervelocity micrometeoroid impact, projectile speeds of about $15\,\mathrm{km\,s^{-1}}$ are required. Below these speeds, the elastic energy of the impact exceeds the nuclear vibration and electron excitation energies and results in a different, less efficient ionization mechanism (evaporation of impurities) than occurs in high-velocity impacts. For this work, the hypervelocity launcher (HVL, also referred to as the three-stage gun launcher) at the Shock and Thermodynamics Applied Research facility at Sandia National Laboratories was used. Combining a light-gas gun projectile with a graded-density pillow to impact a stationary flyer plate, the HVL produces velocities up to $12\,\mathrm{km\,s^{-1}}$. Even at these speeds, the ionization energy requirements for realistic (mostly carbon) micrometeoroids would likely not be met (see Ref. [8]), so a reasonably benign material with a lower ionization potential was selected—in this case, indium. Indium foil of 99.999% purity was selected to minimize the role of impurities in scavenging electrons from the impact plasma.

The RF measurement apparatus is depicted in Fig. 1. The system is designed to contain all electromagnetic emissions from the debris within the sensor itself, thereby maximizing the likelihood of detection. It consists of distinct, isolated low- and high-frequency sensors. Two broadband (1–18 GHz) microwave horns with center ribs form the high-frequency detector, and are connected via shielded unbalanced lines to fast storage oscilloscopes. Four DC plates provide sensitivity in the band below about 400 MHz. The top, bottom, and rear panels connect to fast oscilloscopes, while the front panel is grounded to the mounting plate. The front panel includes a small window over which 0.75 mm In foil mounts. The rear panel is almost fully occupied by a much larger window designed to permit debris to exit the sensor with a minimum of resistance. During the initial part of the measurement, aluminum foil covers this window and acts as part of the sensing plate.

The design of the measuring apparatus was complicated by the complete lack of previous analogous measurements of RF emissions from impact-produced plasmas. It was therefore not known what signal

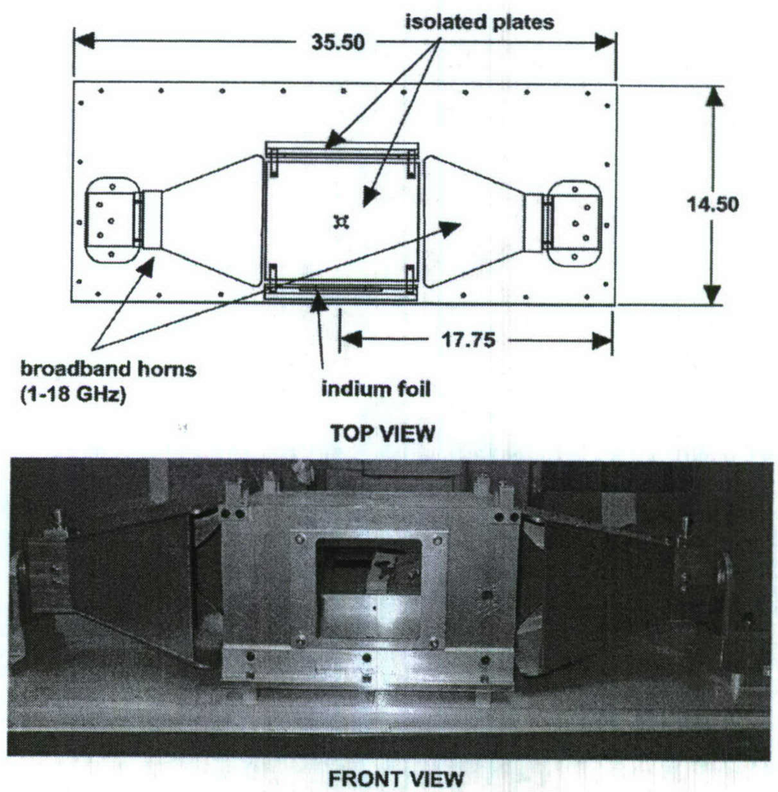

Fig. 1. Schematic top view (top panel) and photographic front view (bottom panel) of the broadband RF antenna apparatus.

strengths to expect, and the device was constructed for maximum sensitivity. Broadband noise tests using a spark gap RF source demonstrated the sensitivity of the horns to frequency content above about 500 MHz, and that of the plates to signals below this range, as expected. The DC plates measure signals effectively to frequencies below 10 MHz, which is far below the requirements for this experiment.

4. Results and discussion

During the initial set of experiments discussed here, five high-velocity impacts were successfully completed. The speeds and other characteristics of these impacts are shown in Table 1. Shot 2 was designated as a control. It used no In foil in an attempt to separate experimental effects from signals produced by the In plasma. Shot 5 attempted to produce a strong secondary impact by replacing the rear aluminum foil with a tungsten sheet.

The data set obtained lacks measurements from the DC plates during the first three shots. Overwhelming signals were repeatedly encountered on these channels, leading to faulting of the data acquisition system and loss of data. Despite efforts to characterize and accommodate these signals without compromising dynamic range, a strong velocity dependence prevented acquisition of usable plate data until the final two shots of the series.

A time series of acquired data typical of these shots is plotted in Fig. 2, which characterizes Shot 4. The raw signals from the broadband horns are shown in the top panel, while the three DC plate channels are plotted in the bottom panel. The initial impact of the flyer plate with the In foil is denoted by the solid vertical line, and is determined very accurately via X-ray imagery. The estimated flight time of the In debris is marked by the vertical broken line, which indicates the initial impact of the debris with the rear panel of the apparatus. The speed estimate of 11 km s^{-1} for the debris is not directly measured in these studies, but based on interferometry measurements in separate experiments [9].

The most dramatic features of Fig. 2 are the strong waveforms appearing on both the horns and the plates before the impact of the flyer plate. The signals also persist long after the In debris cloud has exited the apparatus. These unexpected signals probably originate from two distinct sources: charging of the flyer plate and collection of plasma by the sensor.

Charging of the flyer plate is not a surprising discovery. During its flight through the chamber the flyer plate behaves much like a re-entering spacecraft. Simple friction with the 100 millitorr environment of the open chamber and the hydrogen working gas leads to the formation of a thermal plasma around its leading edge. Charge can be easily picked up by the plate during its journey to the In target. As the flyer approaches, image charges flow through the sensor to or from the ground, registering as a signal on the recording oscilloscopes.

Further evidence of a charged flyer can be seen by focusing on the signals received by the plates prior to impact with the In. Fig. 3 shows the results of a low-frequency spectral analysis on the plate data from Shot 5. Note the strong broadband pulse received on all channels when the flyer is about 17 cm from the target. This pulse is most likely produced by a Paschen discharge between the charged flyer and the grounded chamber. Paschen's relation, as described in Ref. [10], expresses the breakdown voltage of a gas in a uniform electric field as a function of a pressure–distance product. In 100 millitorr air, as found in the experiment chamber, the curve has a minimum at a distance of 5 cm and a potential of about 350 V. The observed broadband spike in the data occurs when the flyer plate is 17 cm from the In target or 5 cm from the last chamber-mounted baffle plate. It is likely, therefore, that the flyer discharged to the baffle plate both before and after passing through it. The initial discharge would not have been visible to the sensor from behind the baffle plate. The minimum

Table 1
Summary of experiment conditions

Shot	Flyer velocity (km s^{-1})	In thickness (mm)	Rear foil (mm)
1	9.468	0.75	0.013 Al
2	9.663	None	0.013 Al
3	10.91	0.75	0.013 Al
4	10.95	0.75	0.013 Al
5	~11	0.75	0.25 W

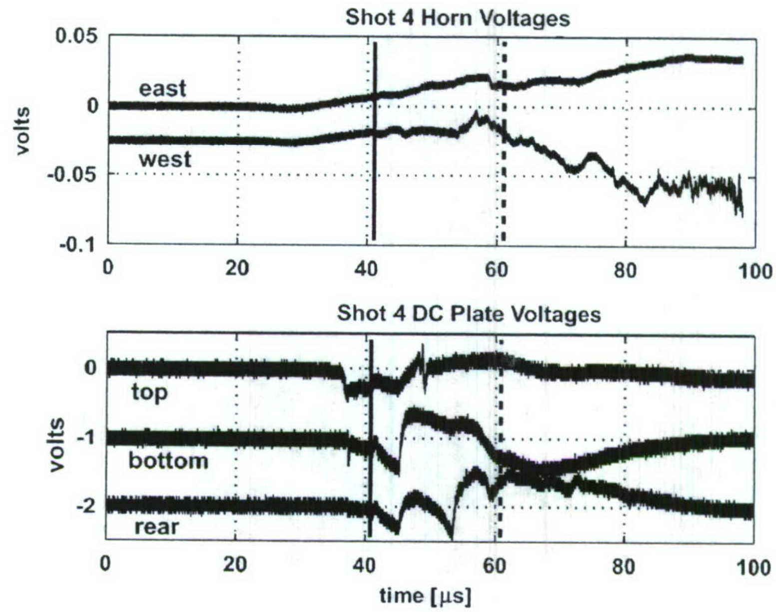

Fig. 2. Waveforms acquired from the horns (top panel) and the plates (bottom panel) during Shot 4. The solid vertical line denotes the impact of the flyer with the In foil. The broken line is the estimated impact of the In debris cloud with the rear panel. Note the strong low-frequency signals beginning prior to impact and persisting long after the In debris cloud is gone. Horn signals are offset by 0.025 V, while plate signals are offset by 1 V.

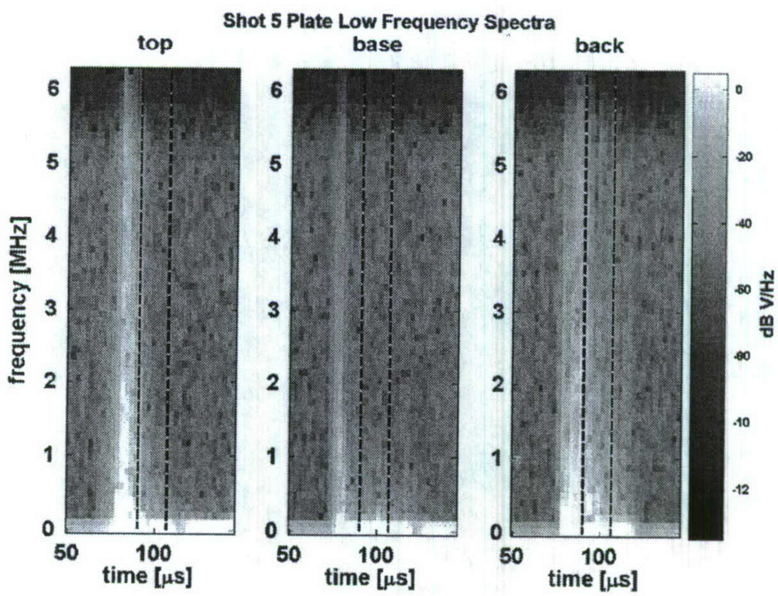

Fig. 3. Spectrogram of the low-frequency portion of the signals recorded from the DC plates during Shot 5. The vertical lines represent the estimated impact times on the indium foil (left line) and the rear panel (right line). Note the strong broadband pulse prior to impact.

required potential of 350 V is consistent with about 10^7 electrons on the flyer plate—a number easily produced by frictional charging.

The large signals recorded from the horns and plates after the charged flyer and In debris have exited the system are likely caused by charged material flowing from the launch site. The launcher system incorporates quantities of polymethylpentene (TPX, a very low density, transparent thermoplastic polyolefin) in the graded

density pillow used to accelerate the flyer plate in a shockless manner. When shocked and relaxed during the shot, TPX completely dissociates and accumulates charge or ionizes. It represents a significant part of the secondary debris cloud in the chamber. This secondary plasma is collected by the surfaces of the broadband sensor, particularly the plates, and the resulting current flow is detected as a low-frequency signal.

During each of the shots, good dynamic range and sensitivity were maintained despite the strong signals produced by the processes described above. In each case, the waveforms were Fourier analyzed to look for evidence of the postulated broadband plasma emissions. Fig. 4 shows the spectrogram of the horn measurements for Shot 4, which is typical of all of the shots. Note that there is no evidence of RF emissions before, during, or after the flyer impact. Fig. 5 plots the corresponding DC plate spectrograms, which also

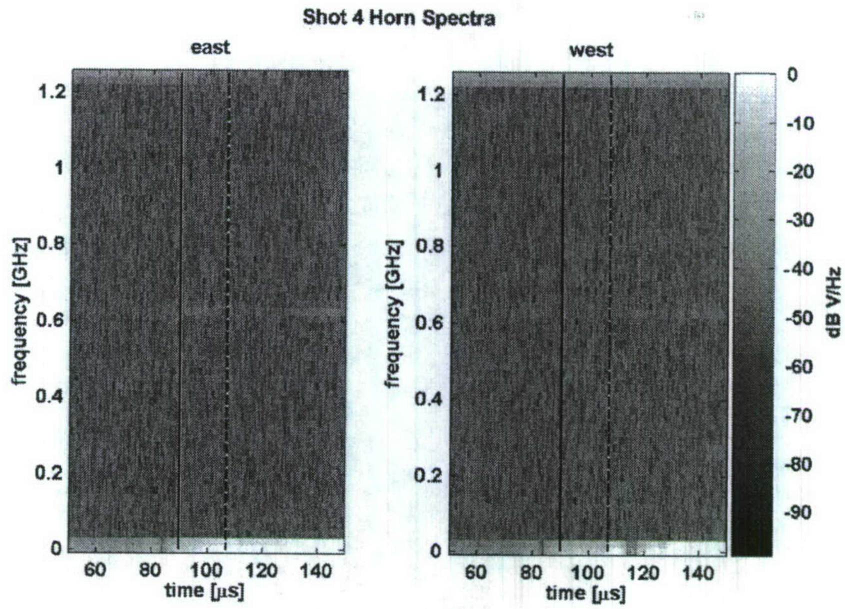

Fig. 4. Spectrogram of the waveforms recorded from the horns on Shot 4. There is no evidence of high-frequency plasma emissions during the shot.

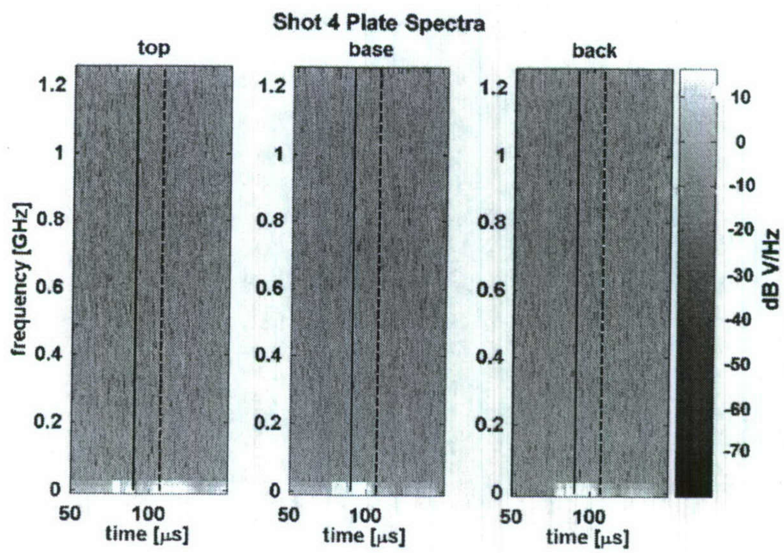

Fig. 5. As Fig. 4, but for the DC plates.

reveal no such signals. In fact, no evidence whatsoever of RF emissions from the In debris cloud was detected during the experiments.

The negative result of the experiment may stem from several factors. First, the In may not be well ionized. Although recent interferometry experiments by Chhabildas and Reinhart [9] have suggested that the In debris includes vaporized material, it is possible that there is insufficient energy in the $\sim 11\,\mathrm{km\,s^{-1}}$ collision to appreciably ionize the metal. Aluminum atoms from the flyer plate may also scavenge any electrons from the debris plasma as quickly as they are created. Finally, since the desired signals are expected to be weak, the large background voltages produced by the charged flyer or the collection of secondary debris plasma electrons may mask them, although the low-frequency nature of these waveforms makes this unlikely.

5. Further experiments

Follow-on experiments will attempt to maximize the chances of producing an In debris plasma, as well as attempting to resolve and mitigate (where possible) the confounding signals seen in the original shots. The HVL will be used in a higher velocity configuration, launching 3 mm diameter flyers at $18\,\mathrm{km\,s^{-1}}$ into thinner In sheets. The sensing apparatus will be placed a few meters downstream of its current position to further discriminate between plasma collection processes (which should be reduced) and charged flyer effects. Magnetic search coils will be added to look for the secondary debris plasma created from the TPX and attempt to characterize it.

Finally, future tests may revisit the assumption that In is effectively easy to ionize and instead utilize more realistic spacecraft materials, such as multi-layer insulation. This could provide insight more directly applicable to hypervelocity micrometeoroid impacts to spacecraft.

6. Conclusions

Impact experiments failed to record any of the postulated RF emissions from an In debris plasma, despite achieving several $11\,\mathrm{km\,s^{-1}}$ impacts. Future experiments will engage the HVL near its maximum velocity capability to determine if a radiating In plasma can be created. Evidence of TPX-derived plasma, charging of the flyer plate, and a possible Paschen discharge in the chamber are nevertheless interesting incidental results. Although these processes would not affect the typical impact experiment concerned with mechanical effects, they are extremely important in planning future experiments involving electrical measurements.

Acknowledgment

The authors gratefully acknowledge the assistance of Dr. Ed Murad of AFRL during the planning stages of these experiments.

References

[1] Love SG, Brownlee DE. A direct measurement of the terrestrial mass accretion rate of cosmic dust. Science 1993;262:550.
[2] Foschini L. Electromagnetic interference from plasmas generated in meteoroid impacts. Europhys. Lett. 1998;43:226.
[3] Chhabildas LC, Kmetyk LN, Reinhart WD, Hall CA. Enhanced hypervelocity launcher: capabilities to $16\,\mathrm{km\,s^{-1}}$. Int. J. Impact Eng. 1995;17:183–91.
[4] Chhabildas LC, Dunn JE, Reinhart WD, Miller JM. Impact technique to accelerate flier plates to velocities over $12\,\mathrm{km\,s^{-1}}$. Int. J. Impact Eng. 1993;14:121–32.
[5] Drapatz S, Michel KW. Theory of shock-wave ionization upon high-velocity impact of micrometeorites. Z. Naturforschung 1974;29A:870–9.
[6] Crawford DA, Schultz PH. Laboratory investigations of impact-generated plasma. J. Geophys. Res. 1991;96:18807–17.
[7] Leung P, Plamp G. Characteristics of RF resulting from dielectric discharges. IEEE Trans. Nucl. Sci. 1992;NS-29:1610.
[8] Ratcliff PR, Alladadi F. Characteristics of the plasma from a $94\,\mathrm{km\,s^{-1}}$ micro-particle impact. Adv. Space Res. 1996;17(12):87–91.
[9] Chhabildas LC, Reinhart WD. private communication, 2005.
[10] Meek JM, Craggs JD. Electrical breakdown of gases, The International Series of Monographs on Physics. Oxford at the Clarington Press; 1953. pp. 82, 83, 96, 98–100.